

A novel spectral broadening from vector–axial-vector mixing in dense matter

Masayasu Harada¹ and Chihiro Sasaki²

¹*Department of Physics, Nagoya University, Nagoya, 464-8602, Japan*

²*Physik-Department, Technische Universität München, D-85747 Garching, Germany*

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The presence of baryonic matter leads to the mixing between transverse ρ and a_1 mesons through a set of $\omega\rho a_1$ -type interactions, which results in the modification to the dispersion relation. We show that a clear enhancement of the vector spectral function appears below $\sqrt{s} = m_\rho$ for small three-momenta of the ρ meson, and thus the vector spectrum exhibits broadening. We also discuss its relevance to dilepton measurements.

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In-medium modifications of hadrons have been extensively explored in the context of chiral dynamics of QCD [1, 2]. Due to an interaction with pions in the heat bath, the vector and axial-vector current correlators are mixed. At low temperatures or densities a low-energy theorem based on chiral symmetry describes this mixing (V-A mixing) [3]. The effects to the thermal vector spectral function have been studied through the theorem [4], or using chiral reduction formulas based on a virial expansion [5], and near critical temperature in a chiral effective field theory involving the vector and axial-vector mesons as well as the pion [6].

It has been derived, as a novel effect at finite baryon density, that a Chern-Simons term leads to mixing between the vector and axial-vector fields in a holographic QCD model [7]. This mixing modifies the dispersion relation of the transverse polarizations and will affect the in-medium current correlation functions independently of specific model dynamics. In this letter we study the effect of the vector–axial-vector mixing to the in-medium spectral functions which is the main input to the experimental observables. We show that the mixing produces a clear enhancement of the vector spectral function which appears below $\sqrt{s} = m_\rho$, and that the vector spectral function is broadened due to the mixing. We will discuss its relevance to dilepton measurements.

At finite baryon density a system preserves parity but violates charge conjugation invariance. Chiral Lagrangians thus in general build in the term

$$\mathcal{L}_{\rho a_1} = 2C \epsilon^{0\nu\lambda\sigma} \text{tr} [\partial_\nu V_\lambda \cdot A_\sigma + \partial_\nu A_\lambda \cdot V_\sigma]. \quad (1)$$

This mixing results in the dispersion relation [7]

$$p_0^2 - \vec{p}^2 = \frac{1}{2} \left[m_\rho^2 + m_{a_1}^2 \pm \sqrt{(m_{a_1}^2 - m_\rho^2)^2 + 16C^2 \vec{p}^2} \right], \quad (2)$$

which describes the propagation of a mixture of the transverse ρ and a_1 mesons with non-vanishing three-momentum $|\vec{p}| = \bar{p}$. The longitudinal polarizations, on the other hand, follow the standard dispersion relation, $p_0^2 - \vec{p}^2 = m_{\rho, a_1}^2$. When the mixing vanishes as $\bar{p} \rightarrow 0$, Eq. (2) with lower sign provides $p_0 = m_\rho$ and it with

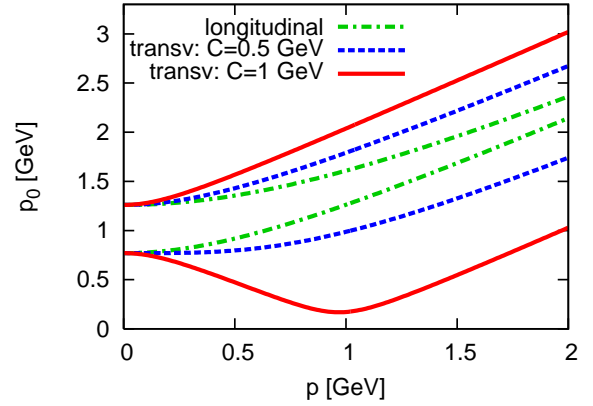


FIG. 1: The dispersion relation of the ρ (lower 3 curves) and a_1 (upper 3 curves) mesons for $C = 0.5$, and 1 GeV.

upper sign does $p_0 = m_{a_1}$. In the following, we call the mode following the dispersion relation with the lower sign in Eq. (2) “the ρ meson”, and it with the upper sign “the a_1 meson”. In a holographic QCD approach the coupling C depends on the baryon density n_B and is found $C \simeq 1 \text{ GeV} \cdot (n_B/n_0)$ with normal nuclear matter density $n_0 = 0.16 \text{ fm}^{-3}$ [7]. Figure 1 shows the dispersion relation (2). For very large \bar{p} the longitudinal and transverse dispersions are in parallel with a finite gap, $\pm C$. The dispersion relation (2) also indicates a possibility of vector condensation for a large C [7].

The vector-current correlation function in matter is decomposed into the longitudinal and transverse parts as

$$G_V^{\mu\nu}(p_0, \vec{p}) = P_L^{\mu\nu} G_V^L(p_0, \vec{p}) + P_T^{\mu\nu} G_V^T(p_0, \vec{p}), \quad (3)$$

with the polarization tensors $P_{L,T}^{\mu\nu}$ and momentum $p^\mu = (p_0, \vec{p})$. Using the bare propagator inverse, $D_{V,A} = s - m_{\rho, a_1}^2 + im_{\rho, a_1} \Gamma_{\rho, a_1}(s)$, G_V^L and G_V^T are expressed as

$$G_V^L = \left(\frac{g_\rho}{m_\rho} \right)^2 \frac{-s}{D_V}, \quad G_V^T = \left(\frac{g_\rho}{m_\rho} \right)^2 \frac{-s D_A + 4C^2 \vec{p}^2}{D_V D_A - 4C^2 \vec{p}^2}, \quad (4)$$

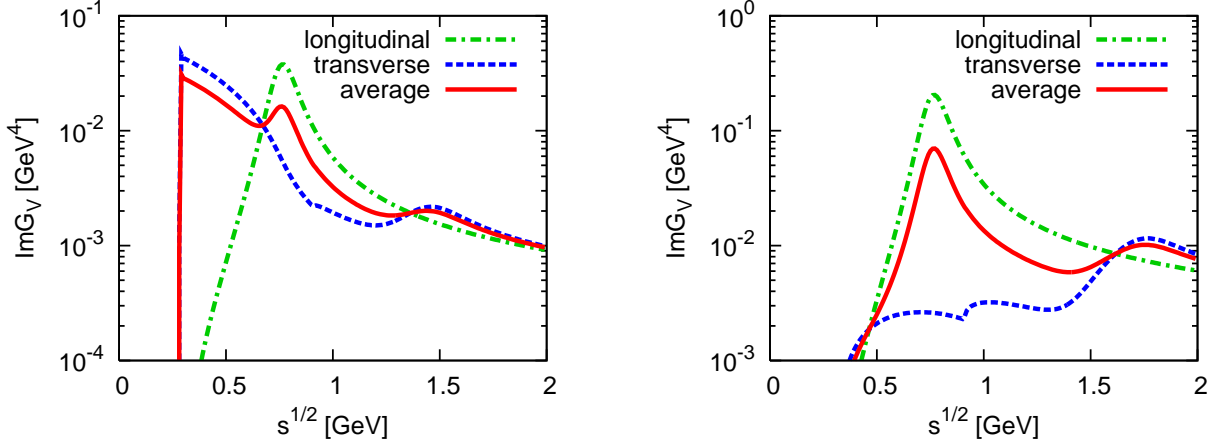


FIG. 2: The vector spectral function for $C = 1$ GeV. The curves of the left figure are calculated integrating over $0 < \bar{p} < 0.5$ GeV, and those of the right figure over $0.5 < \bar{p} < 1$ GeV.

with $s = p^2$ being the squared four-momentum and g_ρ the coupling strength of the ρ meson to the vector current. We have imposed gauge invariance on the vector current to get the form (4). The spin-averaged correlator is given by $G_V = \frac{1}{3} [G_V^L + 2G_V^T]$. The vector spectral function is defined as the imaginary part of the vector correlator (3). We define the integrated spectrum over three momentum by

$$\text{Im}G_V(s) = \int \frac{d^3\vec{p}}{2p_0} \text{Im}G_V(p_0, \vec{p}). \quad (5)$$

Equation (4) indicates that the mixing at finite three momentum \bar{p} affects the real part of the transverse ρ self-energy. We use the vacuum decay widths Γ to illustrate its influence over the spectrum although Γ in dense matter are considered to be broadened [2]. We take the following experimental values for further calculations: $m_\pi = 0.14$ GeV, $m_\rho = 0.77$ GeV, $m_{a_1} = 1.26$ GeV, $g_\rho = 0.119$ GeV², $\Gamma_\rho(s = m_\rho^2) = 0.15$ GeV [8]. For the a_1 decay width we use $\Gamma_{a_1}(s = m_{a_1}^2) = 0.3$ GeV as a typical example.

We show the vector spectral function in Fig. 2. The transverse spectrum presents two bumps due to the mixing: the lower one corresponds to the ρ whose mass is shifted downward, and the upper one to the a_1 whose mass is shifted upward in compared with the longitudinal polarizations (see Fig. 1). Since two pion annihilation is assumed to be dominant in the ρ meson decay, the contribution at low \sqrt{s} is cut off at threshold $\sqrt{s} = 2m_\pi$. Figure 2 (left) shows a clear enhancement of the spectrum below $\sqrt{s} = m_\rho$ due to the mixing. This enhancement becomes much suppressed when the ρ meson is moving with a large three-momentum as shown in Fig. 2 (right). The upper bump now emerges more remarkably and becomes a clear indication of the in-medium effect from the a_1 via the mixing. The presence of the two bumps

in the transverse part leads to some broadening of the spin-averaged spectrum.

For more realistic evaluations one needs to include nuclear many-body dynamics into meson decay widths. This will be another source of in-medium broadening and eventually the vector correlator may not exhibit a clear maximum. Besides the iso-vector ρ - a_1 mesons, the mixing between the ω and $f_1(1285)$ mesons as well as that between the ϕ and $f_1(1420)$ mesons in iso-scalar channel also exists and changes the dispersion relations. This is controlled by the same mixing strength C which can be smaller in three-color QCD than the value predicted in holographic QCD models. In such a case the spectrum enhancement in low \sqrt{s} region becomes more moderate but the effect is still relevant to the vector spectrum of the ρ mesons carrying large \bar{p} . As a result, the averaged spectrum might have a broad bump with its maximum slightly shifted *downward* due to the mixing. Thus, it is expected that those mixing have some relevance to explain in-medium “mass shift” of the ρ , ω and ϕ mesons observed by CBELSA/TAPS and KEK-PS-E325 [9, 10].

As an application of the above in-medium spectrum, we calculate the production rate of a lepton pair emitted from dense matter through a decaying virtual photon. The differential production rate in a medium for fixed temperature T and baryon density n_B is expressed in terms of the imaginary part of the vector current correlator as [2]

$$\frac{dN}{d^4p}(p_0, \vec{p}; T, n_B) = \frac{\alpha^2}{\pi^3 s} \frac{1}{e^{p_0/T} - 1} \text{Im}G_V(p_0, \vec{p}; T, n_B), \quad (6)$$

where $\alpha = e^2/4\pi$ is the electromagnetic coupling constant. The three-momentum integrated rate is given by

$$\frac{dN}{ds}(s; T, n_B) = \int \frac{d^3\vec{p}}{2p_0} \frac{dN}{d^4p}(p_0, \vec{p}; T, n_B). \quad (7)$$

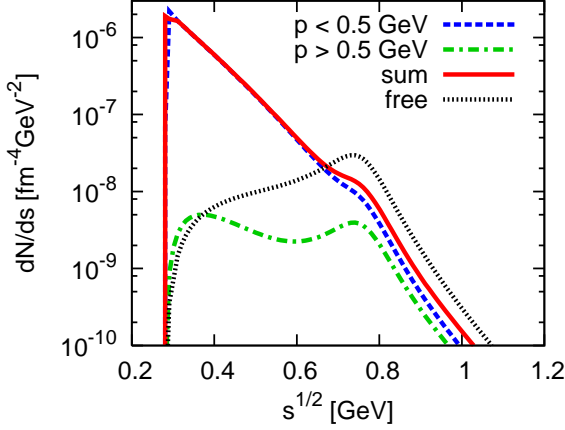


FIG. 3: The dilepton production rate at $T = 0.1$ GeV for $C = 1$ GeV. Integration over $0 < \bar{p} < 0.5$ GeV (dashed) and $0.5 < \bar{p} < 1$ GeV (dashed-dotted) was carried out.

Figure 3 presents the integrated rate at $T = 0.1$ GeV for $C = 1$ GeV. One clearly observes a strong three-momentum dependence and an enhancement below $\sqrt{s} = m_\rho$ due to the Boltzmann distribution function which result in a strong spectral broadening. The total rate is mostly governed by the spectrum with low momenta $\bar{p} < 0.5$ GeV due to the large mixing parameter C . When density is decreased, the mixing effect gets irrelevant and consequently in-medium effect in low \sqrt{s} region is reduced in compared with that at higher density. The calculation performed in hadronic many-body theory in fact shows that the ρ spectral function with a low momentum carries details of medium modifications [11]. One may have a chance to observe it in heavy-ion collisions with certain low-momentum binning at J-PARC, GSI/FAIR and RHIC low-energy running.

It is straightforward to introduce other V-A mixing between ω - $f_1(1285)$ and ϕ - $f_1(1420)$. We use the constant widths of narrow peaked mesons above threshold: $\Gamma_\omega = 8.49$ MeV, $\Gamma_\phi = 4.26$ MeV, $\Gamma_{f_1(1285)} = 24.3$ MeV and $\Gamma_{f_1(1420)} = 54.9$ MeV [8]. The coupling constants of ω and ϕ mesons to the vector current are given by

$$g_\omega = \frac{1}{3} \frac{m_\omega^2}{m_\rho^2} g_\rho, \quad g_\phi = \frac{\sqrt{2}}{3} \frac{m_\phi^2}{m_\rho^2} g_\rho. \quad (8)$$

Figure 4 shows the integrated rate at $T = 0.1$ GeV with several mixing strength C which are phenomenological option. One observes that the enhancement below m_ρ is suppressed with decreasing mixing strength. This forms into a broad bump in low \sqrt{s} region and its maximum moves toward m_ρ . Similarly, some contributions are seen just below m_ϕ . This effect starts at threshold $\sqrt{s} = 2m_K$ in the present analysis because of $\Gamma_\phi(s) = \Theta(s - 4m_K^2) \Gamma_\phi(m_\phi)$. Self-consistent calculations of the spectrum in dense medium will provide a smooth

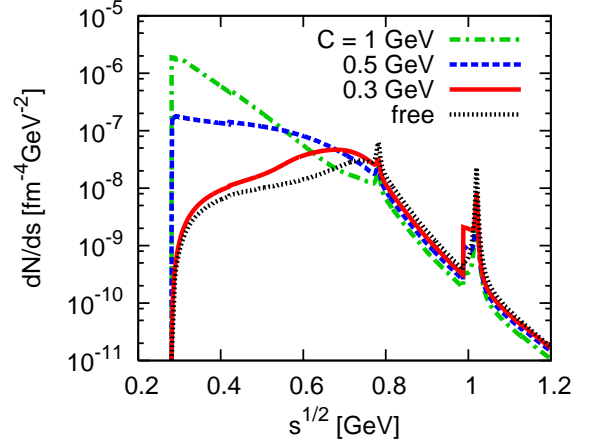


FIG. 4: The dilepton production rate at $T = 0.1$ GeV with various mixing strength C . Integration over $0 < \bar{p} < 1$ GeV was done. Free decay widths are used.

change and this eventually makes the ϕ meson peak somewhat broadened.

The relevance of this mixing in dense matter essentially relies on how the strength C is precisely determined. Holographic QCD approach predicts a strong mixing. However, the models based on the gravity-gauge correspondence are formulated in large N_c limit. Their prediction of observables may have a non-negligible $1/N_c$ correction [12]. This suggests a possibility that C is smaller in realistic QCD. One might consider to replace the mixing term (1) with the ω - ρ - a_1 term which has been shown to arise from the gauged Wess-Zumino-Witten term in chiral Lagrangians [13] or alternatively from the reduction of five-dimensional Chern-Simons term to four dimensions [14],

$$\mathcal{L}_{\omega\rho a_1} = g_{\omega\rho a_1} \langle \omega_0 \rangle \epsilon^{0\nu\lambda\sigma} \text{tr} [\partial_\nu V_\lambda \cdot A_\sigma + \partial_\nu A_\lambda \cdot V_\sigma], \quad (9)$$

where the ω field is replaced with its expectation value given by $\langle \omega_0 \rangle = g_{\omega NN} \cdot n_B / m_\omega^2$. One finds with empirical numbers $C = g_{\omega\rho a_1} \langle \omega_0 \rangle \simeq 0.1$ GeV at normal nuclear matter density. This relatively much weaker mixing has little importance in the correlation functions. It is plausible to assume an actual value of C in QCD in the range $0.1 < C < 1$ GeV since the strong mixing in holographic QCD models contains higher members of Kaluza-Klein (KK) modes other than the lowest ω meson and those higher excitations are embedded in C . Some importance of the higher KK modes *even in vacuum* in the context of holographic QCD can be seen in the pion electromagnetic form factor at the photon on-shell: This is saturated by the lowest four vector mesons in a top-down holographic QCD model [15, 16]. In hot and dense environment those higher members get modified and the masses might be somewhat decreasing evidenced in an in-medium holographic model [17]. This might provide

a strong V-A mixing $C > 0.1$ GeV in three-color QCD and the dilepton measurements may be a good testing ground.

It is also an interesting issue to address a change of the vector correlator with the V-A mixing toward chiral symmetry restoration. The mixing (1) is chirally symmetric and thus does not approach zero toward the chiral restoration in contrast to the vanishing V-A mixing near the critical temperature T_c without baryon density [6]. A spontaneous breaking of Lorentz invariance via the omega condensation could increase the mixing strength C near chiral restoration [18]. Furthermore, if meson masses drop due to partial restoration of chiral symmetry assuming a second- or weak first-order transition in high baryon density but low temperature region, the ground state near the critical point may favor vector condensation even for a moderate mixing strength. This will be reported elsewhere.

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